

Effect of squalene absorption on oxidative stability of highly crosslinked UHMWPE stabilized with natural polyphenols

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ARTICLE INFO

Keywords:
UHMWPE
Lipid
Oxidation
Polyphenol
Irradiation

ABSTRACT

The uptake of synovial lipids into ultra high molecular weight polyethylene (UHMWPE) has been recently related with the *in vivo* and *ex vivo* oxidation of irradiated and remelted UHMWPE. Natural polyphenols have been demonstrated effective in protecting highly crosslinked UHMWPE from oxidation. This manuscript aims to investigate how squalene as a model unsaturated lipid affects the oxidative stability of polyphenol-stabilized highly crosslinked UHMWPE. The irradiated UHMWPE showed less squalene uptake and diffusion in comparison to the unirradiated UHMWPE due to the crosslinked structures in the former. Upon accelerated aging at 70 °C and 5 atm O₂ for different durations, the presence of squalene significantly accelerated the initiation, development and propagation of oxidation for the virgin and irradiated UHMWPE. The presence of antioxidants including natural polyphenols effectively prospected and reduced oxidation of the squalene-doped irradiated UHMWPEs. The oxidation levels and depth of irradiated antioxidant/UHMWPE blends were much less than those for the irradiated UHMWPE. It is concluded that the natural polyphenols are effective in prohibiting oxidation related to the presence of squalene. This finding may be of clinical relevance in terms of stabilization of irradiated UHMWPE against synovial lipids-related oxidation.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) has been the material of choice for total joint implants since the 1960s [1]. The long term oxidation of UHMWPE components remains as one of the most relevant concerns in total joint arthroplasty (TJA) [2–4]. Free radicals generated by radiation sterilization or crosslinking to improve the wear resistance [5] are prone to react with oxygen on shelf or *in vivo* through a cyclic radical process, leading to the degradation of polymer chains and loss of mechanical strength and toughness and wear resistance.

To avoid the UHMWPE oxidation initiated by free radicals, gas sterilization [1], gamma sterilizing in the absence of oxygen [6], or post-irradiation thermal treatments [7–9] have been used to manufacture oxidation resistant UHMWPE. Although the uncrosslinked, non-ionizing gas (e.g., ethylene oxide) sterilized UHMWPE showed undetectable oxidation [10] and slight measurable amounts of oxidation were observed in the retrieved inserts [11], such materials are currently less preferable for medical implants as

a result of their inferior wear resistance [12]. Some studies suggest that gamma sterilizing in the absence of oxygen prevented the shelf oxidation, but did not prevent *in vivo* oxidation [13]. Once it is removed from the package, it will begin to oxidize and degrade [14–16]. Post-irradiation thermal treatments, i.e., remelting or annealing of irradiated UHMWPE, have been conducted to reduce or eliminate the free radicals to improve the oxidation resistance of irradiated UHMWPE [17–19]. However, recent studies reported *in vivo* oxidation of remelted highly crosslinked UHMWPE [20,21], despite that these materials have previously been demonstrated stable against accelerated aging in laboratory tests [22,23]. It has been hypothesized that cyclic loading and/or lipid absorption, are potential mechanisms that alter the stability of UHMWPE [24]. Historically, Costa et al. have demonstrated *in vivo* diffusion of apolar synovial lipids including squalene, cholesterol, and methyl esters of 7-hexadecenoic and cholesterol into UHMWPE components [25]. A recent report based on *in vitro* experiments has suggested that squalene, as well as many other absorbed unsaturated synovial fluid lipids, could be related to the initiation of oxidation of the crosslinked and remelted polyethylenes [26], which may be a new mechanism for the stability loss of the irradiated and remelted polyethylenes [20].

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On the other hand, stabilization of irradiated polyethylene with antioxidants has been widely investigated and has demonstrated promising to avoid post-irradiation thermal treatments [27–29]. Highly crosslinked UHMWPE stabilized with vitamin E has been introduced for clinical use in TJA [30–33]. Moreover, Fu et al. have demonstrated that vitamin E after high temperature melting and high dose irradiation is effective in protecting UHMWPE from oxidation with the presence of squalene [34].

Our previous findings have suggested that natural polyphenols provide improved oxidative stability of highly crosslinked UHMWPE in comparison to the irradiated vitamin E/UHMWPE [27]. It is likely that the reaction of polyphenol molecules to the free radicals interrupts the cyclic oxidation process [35]. It would be of clinical relevance to further investigate how these polyphenol-stabilized highly crosslinked UHMWPE will behave against aggressive oxidative challenging with the presence of an unsaturated model lipid. We hypothesize that trace amount of polyphenols may also offer superior resistance against lipid-related oxidation. In order to examine this hypothesis, high dose irradiated UHMWPE blended with natural polyphenols (i.e., gallic acid and dodecyl gallate) were doped with squalene and challenged with 5 atm oxygen at 70 °C for different durations. Highly crosslinked vitamin E/UHMWPE blends were used as reference.

2. Materials and methods

2.1. Consolidation and electron beam irradiation of antioxidant/UHMWPE blends

Gallic acid, dodecyl gallate (both were purchased from Nanjing Duly Biotech Co., Ltd, China), and vitamin E (Sigma Aldrich, Shanghai, China) were blended with medical grade UHMWPE powders (GUR 1050, Orthoplastics, UK) at antioxidant (AO) concentrations of 0.23, 0.46, 1.1, 2.3, and 6.9 mmol/L. The blended powders were preheated at 200 °C in a vacuum oven before consolidation at 190 °C and 10 MPa for 10 min [27]. The consolidated blocks were vacuum-packaged and irradiated at 30 kGy/pass to total doses of 60 and 90 kGy by using a 10 MeV electron beam (Huaneng Electron Accelerator Company, Shaoxing, China). The sample temperature after each irradiation run was no higher than 50 °C. Cubes ($1 \times 1 \times 1 \text{ cm}^3$) were machined from these irradiated blocks for doping with squalene and accelerated aging.

2.2. Doping in squalene (SQ)

Cubes ($1 \times 1 \times 1 \text{ cm}^3$) of unirradiated, 90 kGy irradiated virgin and AO-blended UHMWPE were immersed in preheated squalene (Sigma Aldrich, Shanghai, China) at 120 °C for 2, 4, 8, and 24 h in a convection oven. Subsequently, the samples were taken out of the squalene bath and cooled down to room temperature. Finally, the excessive squalene on sample surfaces were wiped with cotton gauze.

Gravimetric changes as a result of doping were determined by weighing the cubes before and after doping by using a 0.01 mg balance (Sartorius BT125D, Goettingen, Germany). The percentage weight changes are used to compare the squalene absorption for different materials.

2.3. Accelerated aging of irradiated polymer materials

Squalene-doped irradiated cubes ($1 \times 1 \times 1 \text{ cm}^3$) were aged for 4, 7, 10, 14, 21, and 28 days in a pressure chamber with 5 atm oxygen at 70 °C. Squalene-free cubes were aged under the same conditions for 28 days as control.

2.4. Microscopic Fourier transform infrared (FTIR) spectroscopy

The above prepared sample cubes were cut half apart and microtomed into 100 μm thick slices by using an ERM 3000 Semi-automatic Rotary Microtome (Hao Si Lin Medical Instrument Co., Ltd., Changzhou, China). The slices were line-scanned across in transmission mode by using a Cary 610 microscope equipped with a Cary 640 FTIR spectrometer (Agilent, Australia). Each spectrum was recorded as an average of 32 individual infrared scans from 400 to 4000 cm^{-1} at a resolution of 4 cm^{-1} . The content of squalene was indexed by normalizing the squalene band at 1151 cm^{-1} (1134–1168 cm^{-1}) against the polyethylene skeletal band at 1895 cm^{-1} (1850–1985 cm^{-1}). This squalene index (I_{SQ}) was plotted as a function of position across the cubes, generating a squalene distribution profile for each sample. The slices of doped and aged samples were refluxed in hexane for 24 h to remove small molecule oxidation products and then dried in vacuum for 24 h at room temperature. Finally, these post-hexane slices were microscopic FTIR scanned in transmission mode in order to determine the oxidation profiles. Each IR spectrum was normalized by using the 2018 cm^{-1} band (CH_2 twisting) as the internal reference to an absorbance of 0.05 for a film thickness of ca. 100 μm [36]. The oxidation index (I_{OXI}) were calculated as the ratio of the peak area at 1718 cm^{-1} (1680–1820 cm^{-1} , carbonyl stretching) to that at 1368 cm^{-1} (1370–1390 cm^{-1} , polyethylene end methyl) as per ASTM F2102-01. The average surface oxidation index was defined as the average of the oxidation indices of the first 1.5 mm from the sample surface.

3. Results and discussion

3.1. Squalene doping and diffusion

Squalene doping was conducted at 120 °C to unirradiated, 60, and 90 kGy irradiated UHMWPE with or without antioxidants. The weight gain values of these polyethylenes after 2 h-doping are summarized in Table 1. Moreover, the percentage weight changes of these polymers are compared in Fig. 1 as there are differences in the initial weight of the cubes. The irradiation dose or crosslink density has an influence on the squalene uptake. First, for each group containing a specific antioxidant concentration, the squalene uptake was less with a higher irradiation dose ($p < 0.05$). The squalene absorption for the unirradiated polymers was about 40% higher than for the 90 kGy irradiated materials. Second, the squalene uptake of the materials with antioxidants was higher than those of virgin UHMWPE at each irradiation dose. The vitamin E-blended UHMWPE showed the highest squalene uptake among the irradiated AO/UHMWPEs. Third, with a higher antioxidant concentration, the squalene uptake was less. It has been reported that the irradiated vitamin E/UHMWPE blends at relatively high vitamin E concentrations showed lower crosslink densities than the irradiated counterparts containing gallic acid (GA) and dodecyl gallate (DG) [27] and irradiated virgin UHMWPE [37,38]. These results suggest that it would be difficult for squalene to diffuse into a densely crosslinked polymer network.

In doped UHMWPE, squalene showed characteristic absorbances at 1668 cm^{-1} ($\text{C}=\text{C}$ stretching) and 1151 cm^{-1} ($\text{C}-\text{H}$ bending) in addition to those of polyethylene (Fig. 2(a)). These bands are normalized against the CH_2 band of polyethylene at 1895 cm^{-1} and subtracted by the normalized spectrum of virgin UHMWPE. The difference spectrum shows the characteristic absorbances of squalene (Fig. 2(a)). By performing a line scan of squalene-doped samples with a microscopic FTIR, the spatial-resolved difference spectra show a decay of the 1151 cm^{-1} band

Table 1

Mass and percentage mass changes of different 1 cm³ UHMWPE samples immersed in squalene at 120 °C for 2 h.

UHMWPE materials	Irradiation dose (kGy)	Mass change (mg)	Percentage mass change (%)
No antioxidant	0	33.4 ± 1.6	3.21 ± 0.09
	60	NA	NA
	90	23.0 ± 1.6	1.99 ± 0.07
Vitamin E	0	36.1 ± 1.3	2.98 ± 0.17
	60	31.9 ± 3.3	2.52 ± 0.16
	90	28.6 ± 1.8	2.06 ± 0.18
	0	36.7 ± 2.3	3.52 ± 0.03
	60	29.4 ± 1.4	2.54 ± 0.16
	90	24.4 ± 1.1	2.18 ± 0.08
2.3 mmol/L	0	35.5 ± 4.1	3.08 ± 0.31
	60	32.4 ± 2.3	2.83 ± 0.16
	90	28.9 ± 2.1	2.44 ± 0.31
6.9 mmol/L	0	31.3 ± 0.7	2.80 ± 0.06
	60	27.8 ± 1.4	2.46 ± 0.15
	90	21.9 ± 1.2	1.98 ± 0.11
Gallic acid	0	40.5 ± 3.2	3.45 ± 0.03
	60	30.6 ± 1.4	2.49 ± 0.06
	90	25.6 ± 1.7	2.37 ± 0.15
2.3 mmol/L	0	35.6 ± 3.4	3.08 ± 0.24
	60	29.7 ± 2.6	2.41 ± 0.20
	90	25.3 ± 0.9	1.98 ± 0.01
Dodecyl gallate	0	43.6 ± 2.9	3.03 ± 0.09
	60	27.9 ± 1.5	2.41 ± 0.11
	90	25.8 ± 4.2	2.08 ± 0.20
2.3 mmol/L	0	39.6 ± 2.2	2.95 ± 0.26
	60	29.8 ± 2.2	2.46 ± 0.08
	90	24.1 ± 2.6	2.17 ± 0.12
6.9 mmol/L	0	43.1 ± 3.6	3.01 ± 0.17
	60	30.7 ± 1.1	2.53 ± 0.06
	90	27.4 ± 2.8	2.25 ± 0.17

(or squalene concentration) from the free surface (0 μm) toward the internal bulk (Fig. 2(b)). Hereafter, the 1151 cm⁻¹ band is used to index the squalene levels in doped polyethylenes.

The irradiation dose showed remarkable influences on the uptake and diffusion of squalene. Fig. 3(a) presents representative squalene profiles of the unirradiated and 90 kGy irradiated UHMWPE and VE/UHMWPE after doping and diffusion in hot squalene for 24 h. The unirradiated UHMWPE and VE/UHMWPE

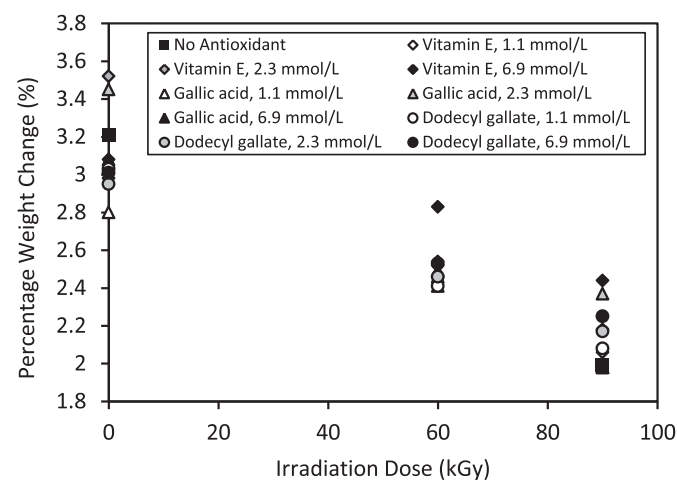


Fig. 1. Percentage weight change of squalene-doped irradiated virgin UHMWPE and antioxidants/UHMWPE blends with 0, 60, and 90 kGy doses. The standard errors are listed in Table 1 and omitted in this diagram for clarity.

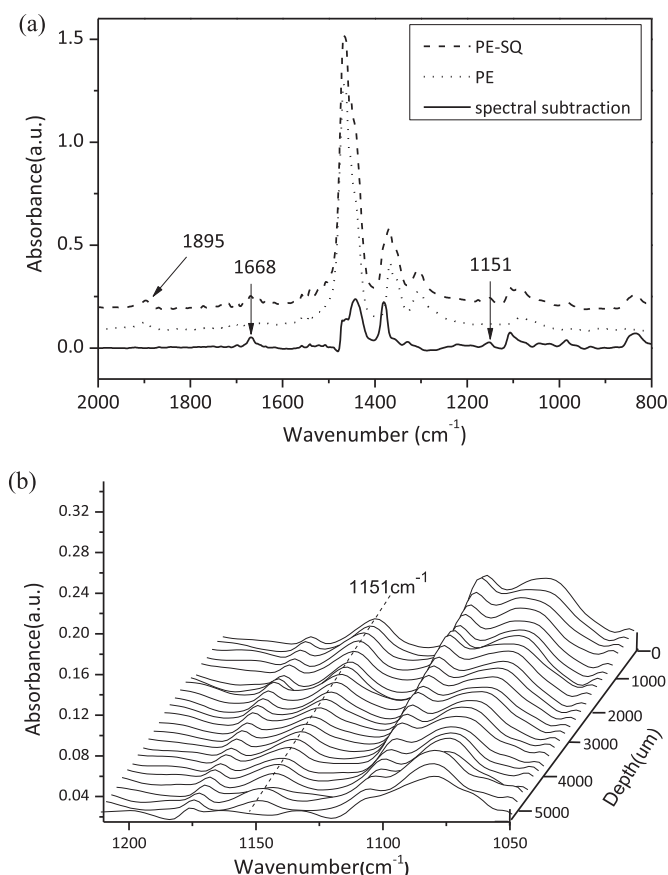


Fig. 2. (a) Representative transmission infrared spectra of UHMWPE specimens immersed in squalene (SQ) at 120 °C for 2 h, and (b) FTIR line scan spectra of squalene-doped UHMWPE.

exhibited identical squalene uptake and diffusion profiles (Fig. 3(a)). Squalene diffused into more than 5 mm into the samples. In contrast, the 90 kGy irradiated polyethylene and blends showed a lower squalene uptake. The squalene diffusion depth into the irradiated UHMWPE was about 2.8 mm, close to that for the 90 kGy irradiated VE/UHMWPE (Fig. 3(a)). The squalene uptake for the irradiated UHMWPE was lower than that for the irradiated VE/UHMWPE, due to the higher crosslink density of the former [27].

The diffusion of squalene into UHMWPE basically obeys the Fick's second law of diffusion. Accordingly, curve fitting and analysis were conducted for the squalene profiles in Fig. 3(a). At 120 °C, the diffusion coefficients of squalene (D_{SQ}) in unirradiated UHMWPE and VE/UHMWPE were 3.3×10^{-5} mm²/s. In contrast, the D_{SQ} values in 90 kGy irradiated UHMWPE and VE/UHMWPE were 1.0×10^{-5} mm²/s and 2.0×10^{-5} mm²/s, respectively. The semi-crystalline nature of UHMWPE and the crosslinking in the amorphous phase will affect squalene diffusion. Crystalline regions are deemed to hinder the diffusion of molecules by restricting the diffusion pathways [32]. Moreover, our findings show that the weight changes and the diffusion coefficient difference between the unirradiated UHMWPE and irradiated UHMWPE were very significant for squalene doping, which indicates that the cross-linked network in the amorphous phase may unfavour squalene diffusion. Moreover, the diffusion depth increased over time from about 1.5 mm at 4 h to 2 mm at 8 h and 5 mm at 24 h (Fig. 3(b)).

It is interesting to observe that the surface squalene concentration appeared independent on the doping time, probably indicating a saturation absorption on surface. For a specific sample, e.g.,

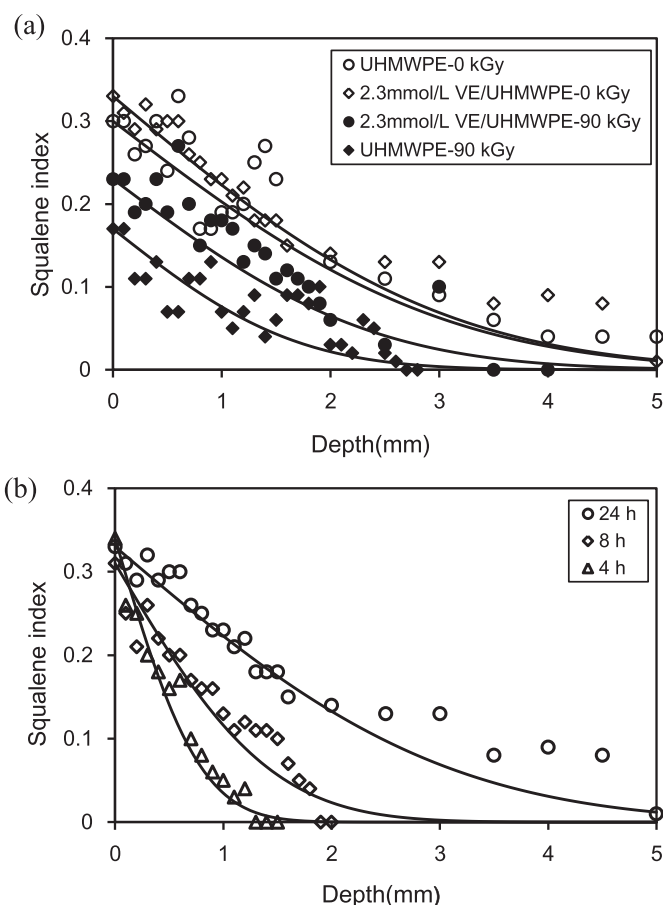


Fig. 3. Squalene index profiles of (a) unirradiated and irradiated virgin and vitamin E (VE) blended UHMWPEs at 120 °C for 24 h, and (b) the unirradiated 2.3 mmol/L VE/UHMWPE after doping at 120 °C for 4, 8, and 24 h.

the 90 kGy irradiated 2.3 mmol/L DG/UHMWPE cube, the total squalene uptake at 24 h was 25.6 ± 1.7 mg, or an overall squalene concentration of 62.3 mmol/L, which is much higher than the DG concentration. It is roughly estimated that the surface squalene concentration is more than one magnitude of order higher than the antioxidant concentration. Therefore, it is reasonable to believe that the absorbed squalene is adequate to exhaust the antioxidants to induce severe oxidation of UHMWPE upon accelerated aging.

3.2. Oxidation of irradiated virgin and antioxidant-containing UHMWPE with the presence of squalene

To examine the effect of squalene on the oxidation of 90 kGy irradiated AO/UHMWPE blends, cubic samples doped with squalene at 120 °C for 2 h were cooled to room temperature and then aged at 70 °C in 5 atm O₂ for 14 days (ASTM F2003). Previous study showed undetectable oxidation of irradiated AO/UHMWPE after accelerated aging according to ASTM F2003 [27]. After aging with the presence of squalene, IR scans across the thin slices showed oxidation gradients from the free surface toward the sample bulk, as indicated by the decaying oxidation product band centered at 1718 cm⁻¹ (Fig. 4(a)). This absorbance is a sum of oxidation products from both polyethylene and squalene. Hexane extraction was conducted on the thin slices to remove the oxidation products from squalene. The spectra of samples after hexane extraction (post-hexane) showed lower absorbances at 1718 cm⁻¹ than for the pre-hexane ones (Fig. 4(b)). All the results reported hereafter are based on the post-hexane IR spectra unless otherwise specified.

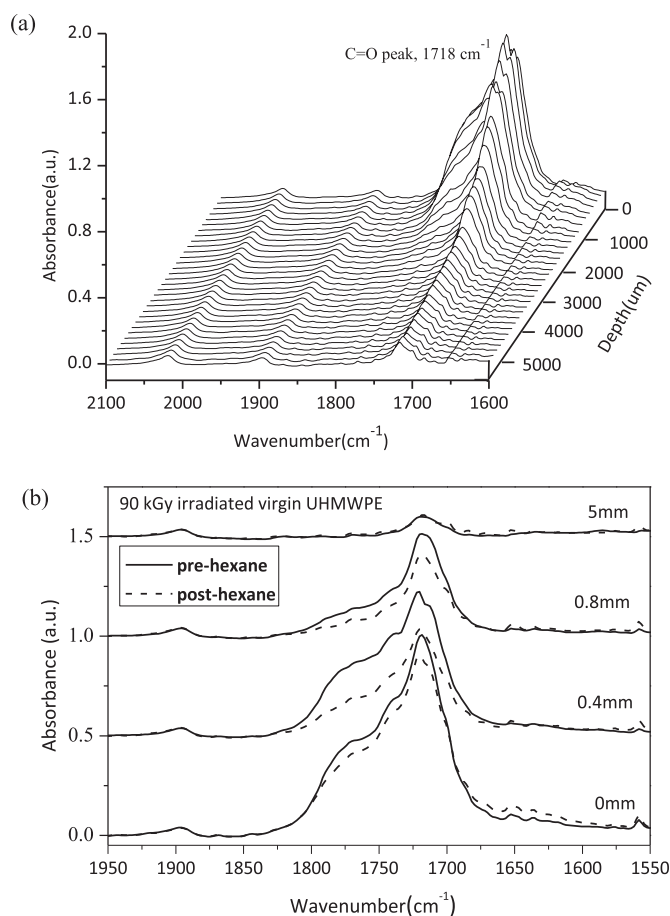


Fig. 4. (a) Transmission FTIR line scan spectra of squalene-doped UHMWPE after accelerated aging at 70 °C in 5 atm oxygen for 14 days. (b) The carbonyl IR spectra at different depth of a squalene-doped irradiated UHMWPE after accelerated aging. The solid and dashed lines represent the spectra before (pre-) and after (post-) hexane extraction to remove extractables.

Fig. 5 shows the oxidation profiles of irradiated AO/UHMWPE doped with squalene and aged in 5 atm O₂ at 70 °C for up to 14 days. The irradiated VE/UHMWPE and DG/UHMWPE with 0.23 mmol/L antioxidants showed no detectable oxidation before aging and slight surface oxidation (depth ~ 1 mm) after 14 day aging (Fig. 5(a and b)). In contrast, the irradiated GA/UHMWPE showed remarkable oxidation (Fig. 5(c)), probably due to the relatively low antioxidation activity of GA in UHMWPE [35]. With the presence of squalene, severe surface oxidation occurred and proceeded toward the cube bulk over time (Fig. 5(a–c)). The average surface oxidation levels increased linearly over time and appeared almost independent on the chemistry of antioxidants (Fig. 5(d)). On the other hand, the oxidation depth for all samples increased over time. The fact that the oxidation levels of squalene-doped samples aged for 4 day are much higher than those of squalene-free samples aged for 14 days indicates a strong relation of squalene absorption to the oxidation of these antioxidant-stabilized UHMWPE.

Fig. 6 summarizes the evolution of the average surface oxidation levels over time for the 90 kGy irradiated AO/UHMWPE with different antioxidant concentrations. The squalene uptake for all these samples after 2 h-doping were almost the same. For 90 kGy irradiated VE/UHMWPE, the surface oxidation levels were lower with higher vitamin E concentrations (Fig. 6(a)). With 1.1 mmol/L vitamin E, no detectable oxidation occurred until day 10. The

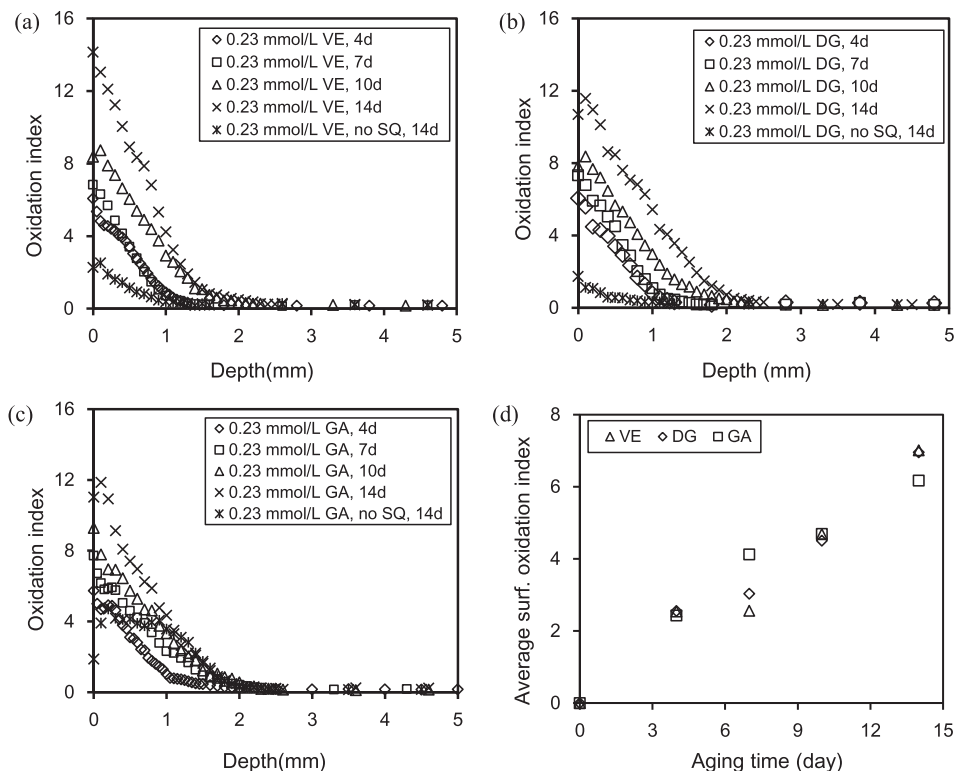


Fig. 5. Oxidation profiles of 90 kGy irradiated UHMWPE doped with squalene (SQ) and aged at 70 °C and 5 atm oxygen for 4, 7, 10, and 14 days. The irradiated UHMWPE materials contain 0.23 mmol/L (a) vitamin E (VE), (b) dodecyl gallate (DG), and (c) gallic acid (GA). (d) The average surface oxidation index (in the first 1.5 mm from the surface) of 90 kGy irradiated 0.23 mmol/L AO/UHMWPE as a function of aging time.

oxidation initiation was further postponed to day 14 for 2.3 mmol/L VE. No oxidation was detectable with 6.9 mmol/L VE at day 28 (Fig. 6(a)). Similarly, oxidation was also retarded by the presence of DG (Fig. 6(b)) and GA (Fig. 6(c)). According to these results, 2.3 mmol/L antioxidants are adequate to inhibit squalene-related surface oxidation for 14 day aging as per ASTM F2003.

Fig. 7 compares the post-hexane oxidation profiles of the aged squalene-doped irradiated AO/UHMWPE blends with different antioxidant concentrations. With the antioxidant concentration increasing from 0.23 mmol/L to 0.46, 1.1, 2.3, and 6.9 mmol/L, the oxidation levels decreased at the surface and in the bulk. The oxidation levels became very low with the presence of 2.3 mmol/L antioxidants. The effect of antioxidant concentration on the average surface oxidation index at day 14 is shown in Fig. 7(d). At a given concentration, GA gives the highest oxidation level, while VE and

DG are close to each other. No detectable oxidation was found for the irradiated UHMWPE with AO concentrations above 2.3 mmol/L DG.

Fig. 8 compares the oxidation profiles of squalene-doped irradiated UHMWPE blends with different antioxidants after accelerated aging. First, the irradiated AO/UHMWPE blends doped with squalene showed lower oxidation levels than for the irradiated virgin UHMWPE doped with squalene. For the antioxidant-blended UHMWPE, the I_{OxI} was less than the virgin polyethylene. The 90 kGy irradiated virgin polyethylene showed the highest I_{OxI} , while the UHMWPE blends with 1.1 and 2.3 mmol/L antioxidant had relative low I_{OxI} values. Furthermore, there was no measurable oxidation for the 2.3 mmol/L DG/UHMWPE, which suggests that DG is more potent than VE and GA in stabilizing the irradiated polyethylene. Although there existed surface oxidation of VE- and GA-

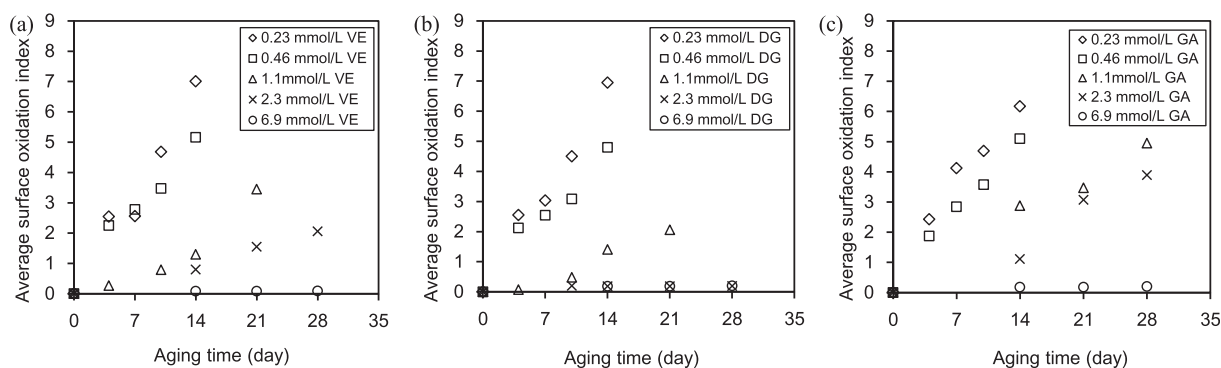


Fig. 6. The average surface oxidation indices over aging time for the 90 kGy irradiated (a) VE/UHMWPE, (b) DG/UHMWPE, and (c) GA/UHMWPE with different concentrations and doped with squalene at 120 °C for 2 h.

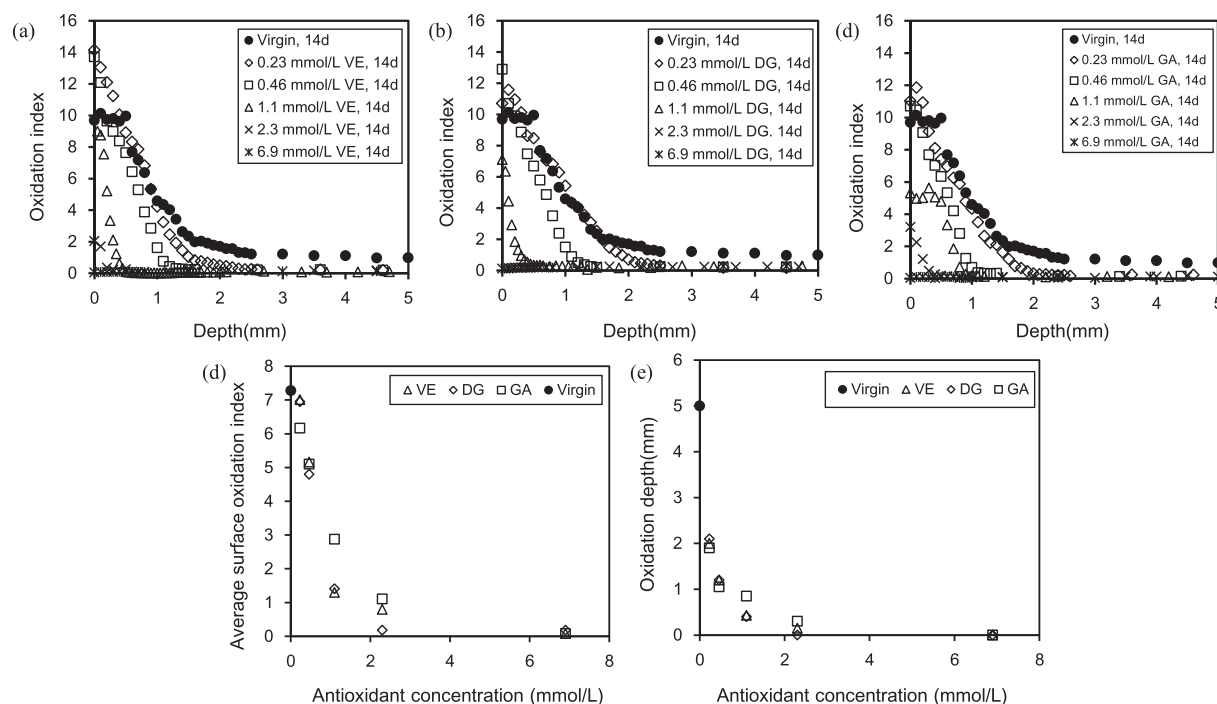


Fig. 7. The oxidation profiles of 90 kGy irradiated (a) VE/UHMWPE, (b) DG/UHMWPE, and (c) GA/UHMWPE after squalene doping and accelerated aging for 14 days with different antioxidant concentrations. (d) The antioxidant concentration dependence of the average surface oxidation indices of these aged samples. (e) The antioxidant concentration dependence of oxidation penetration depth (defined as the forefront with an oxidation index of 0.5) of these aged samples.

blended samples, a stronger stabilization at the cubic center was achieved compared to the virgin PE.

Previous studies have reported the effective stabilization of irradiated high temperature melted vitamin E/UHMWPE blends doped with squalene although some of vitamin E has changed the chemical structure upon irradiation [34]. The resonant structures of irradiated vitamin E have been reported potent in stabilization of irradiated UHMWPE [39]. Recently, we have also reported that two polyphenols (i.e., gallic acid and dodecyl gallate) are potent in stabilisation of highly crosslinked UHMWPE and even provide prolonged protection of irradiated UHMWPE against aggressive *in vitro* oxidative challenges at low antioxidant concentrations in comparison to their vitamin E counterparts [27]. In the current work, our results suggest that the natural polyphenols offer superior resistance against oxidation at the presence of squalene, a model lipid that has been used by Oral et al. to simulate the lipid-related oxidation of polyethylene [26]. This study is effective in distinguishing the oxidation resistance of these antioxidants at a relatively short experimental time scale. At a given antioxidant concentration, the oxidation initiation time and oxidation penetration depth are two important parameters to assess the potency of the antioxidants by comparing the oxidation levels and oxidation profiles. To this end, the DG/UHMWPE blends showed the lowest oxidation levels and penetration depth while the GA/UHMWPE blends showed the highest oxidation levels and penetration depth among the antioxidant/UHMWPE blends at 1.1 mmol/L (Fig. 8(a)). These 90 kGy irradiated materials hardly oxidize with the presence of 2.3 mmol/L DG after accelerated aging for 14 days (Figs. 7(b) and e), 8(b)). This irradiation dose is close to those for the highly crosslinked UHMWPE materials for clinical use. Thus, the results presented in this study may have clinical relevance in terms of oxidative stability.

The clinical relevance of these results, however, is limited in at least three aspects. First, the oxygen concentration and

temperature under clinical conditions are much lower than the current experimental conditions. Thus, the real-time oxidation *in vivo* or *ex vivo* would be much slower than what we observed under *in vitro* accelerated aging conditions. There is, however, no direct correlation between the accelerated aging and the real-time oxidation, which could otherwise help predict the oxidative stability of the highly crosslinked UHMWPE components in the long term. Second, the concentration of unsaturated lipids in the synovial fluids and amount diffused into the UHMWPE components are much lower than the squalene model used in this study. On the other hand, the accelerated aging temperature (70 °C) and oxygen concentration are much higher than those available in the body. The *in vivo* lipid oxidation, if any, must be much slower than those for the accelerated aging study. In fact, it is not clear how the absorbed lipids affect the *in vivo* oxidation and performance of highly crosslinked and remelted UHMWPE components, although *ex vivo* stability loss of irradiated and remelted UHMWPE components might be attributed to the absorbed lipids. Third, the chemistry and amount of unsaturated lipids diffused into UHMWPE components [25] are more complicated than the squalene model investigated in this study. Moreover, the synovial lipids may vary among individuals, which may complicate the oxidation mechanisms. In fact, it remains unclear how the synovial lipids diffused into the UHMWPE components affect their oxidative stability over long term clinical service.

4. Conclusions

This study presents the experimental modeling of the absorption of synovial lipids into highly crosslinked UHMWPE with antioxidants. The absorbed squalene deteriorates the oxidation stability of all the highly crosslinked UHMWPE and antioxidant/UHMWPE blends. Importantly, our results demonstrate that gallic acid and dedecyl gallate provide outstanding protection of highly

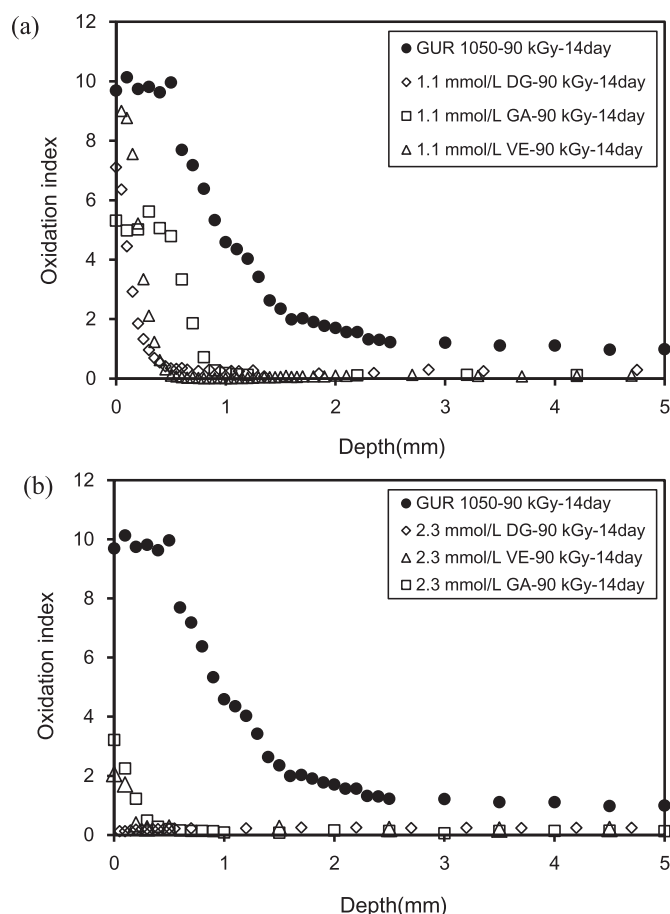


Fig. 8. Oxidation profiles of 90 kGy irradiated UHMWPE blends with (a) 1.1 mmol/L and (b) 2.3 mmol/L antioxidants after squalene doping and accelerated aging for 14 days.

crosslinked UHMWPE against the squalene-related oxidation. Our hypothesis tested positive. Both the oxidation levels and penetration depth are much lower than for the irradiated virgin UHMWPE. All of the antioxidants at 2.3 mmol/L provide sufficient protection to squalene-doped highly crosslinked UHMWPE against accelerated aging for 14 days, without showing detectable oxidation by FTIR.

Acknowledgment

This work was supported by the Hundred Talents Program of the Chinese Academy of Sciences (J. F.), the Natural Science Foundation of China (Nos. 21004074, 212101064), and the Zhejiang Provincial Natural Science Foundation of China (No. LR13B040001).

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